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Effect of rewetting degraded peatlands on carbon fluxes: a meta-analysis

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Abstract

Numerous studies claim that rewetting interventions reduce CO_2 and increase CH_4 fluxes. To verify the claim, we conducted a systematic review and meta-analysis of the effects of rewetting on CO_2 and CH_4 fluxes and dissolved organic carbon (DOC). We identified 28 primary articles eligible for meta-analysis, from which we calculated 48 effect sizes for CO_2 emissions, 67 effect sizes for CH_4 emissions, and 5 effect sizes for DOC. We found that rewetting significantly decreased CO_2 fluxes, with temperate zones showing the highest Hedges' g effect size (-0.798 ± 0.229), followed by tropical (-0.338 ± 0.269) and boreal (-0.209 ± 0.372) zones. Meanwhile, rewetting increased CH_4 fluxes, with the highest Hedges' *g* effect size shown in temperate zones (1.108 ± 0.144), followed by boreal (0.805 ± 0.183) and tropical (0.096 ± 0.284) zones. In addition, based on yearly monitoring after rewetting, the CH_4 emissions effect size increased significantly over the first 4 years ($r^2 = 0.853$). Overall, the rewetting intervention reduced CO_2 emissions by -1.43 ± 0.35 Mg CO_2–C ha^{-1} $year^{-1}$, increased CH_4 emissions by 0.033 ± 0.003 Mg CH_4–C ha^{-1} $year^{-1}$, and had no significant impact on DOC. To improve the precision and reduce the bias of rewetting effect size quantification, it is recommended to conduct more experimental studies with extended monitoring periods using larger sample sizes and apply the before-after control-impact study design, especially in boreal and tropical climate zones.

Keywords Drainage · Effect size · Avoided CO_2 emissions · Peatland restoration · DOC

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1 Introduction

Peatland ecosystems contain large amounts of carbon in the form of soil organic matter. In pristine peatland ecosystems, the organic matter accumulation rate from net primary production exceeds the decomposition rate due to nutrient-poor waterlogged soil (Frolking et al. 2010). Therefore, pristine peatland ecosystems function as net carbon sinks. However, these ecosystems have been degraded and deforested for decades. This degradation process typically involves drainage, which lowers the groundwater level (GWL) and eventually increases the CO_2 emissions (Page et al. 2009). In the drained peatlands, CO_2 emission is the major component of the greenhouse gas (GHG) fluxes (Beyer et al. 2020; Hergoualc'h & Verchot, 2014; Jauhiainen et al., 2019). In comparison, the CH_4 emission in drained peatlands is almost negligible or decreases (Inubushi et al., 2005). Therefore, a management intervention to reduce CO_2 emissions from drained peatlands is needed to maintain global warming below 2 °C (Leifeld et al. 2019).

The severity of peatland degradation varies from site to site. However, since the degradation mainly involves the drainage of intact peatlands, restoration of degraded peatlands typically involves rewetting interventions to restore the GWL and reduce CO_2 emissions (Ojanen & Minkkinen, 2020; Tanneberger et al. 2021). Rewetting is the deliberate action of raising the GWL in a previously drained peatland ecosystem. Drained peatland is deemed to be a rewetted peatland ecosystem if the annual average GWL is equal to or shallower than 30 cm ($\leq$30 cm) below the peat surface (IPCC 2014). To date, most peatland rewetting targets reducing or even avoiding CO_2 emissions as a significant GHG component (Beyer et al. 2020). Since rewetting alters the peatland condition from a drained to a rewetted state, the abiotic environment changes immediately. In contrast, the biotic and chemical environment changes over a longer period of time (Negassa et al. 2019). The higher average GWL in the rewetted state increases the anoxic zone (catotelm layer) and decreases the peat layer's oxic zone (acrotelm layer). A larger anoxic zone reduces the peat decomposition process by aerobic microbial activity, but it can also increase the methanogenesis process (Zhong et al. 2020). As such, CO_2 emissions are expected to be avoided or reduced, while CH_4 emissions from methanogenesis increase in rewetted peatlands. However, the effect of rewetting on DOC concentration is still uncertain (Haddaway et al. 2014).

Recent primary studies on chamber-based CO_2 emissions on peatlands have shown a negative relationship between CO_2 emissions and GWL; CO_2 emissions decreased as GWL increased (Luan et al. 2018; Murdiyarso et al., 2019; Renou-Wilson et al. 2018). These studies also found that rewetted peatlands have lower CO_2 emissions than their drained counterparts. In contrast, CH_4 emissions tend to increase as GWL rises due to the rewetting intervention (Jordan et al. 2016; Kandel et al. 2020). These empirical findings were confirmed by several review studies by Couwenberg et al. (2010) and Jauhiainen et al. (2016) on rewetted tropical peatlands and Wilson et al. (2016a) on rewetted temperate and boreal peatlands. However, those review studies did not directly compare the effect of the rewetting intervention on carbon emissions between control and intervention sites individually and overall. In previous review studies, the collected data (i.e., CO_2 and CH_4 emissions and DOC) from different land covers were plotted versus GWL to evaluate the effect of water table fluctuation on CO_2 or CH_4 emissions. This approach could demonstrate and describe the general impact of GWL fluctuation on the carbon emissions (Jauhiainen et al. 2016; Zhong et al. 2020). Moreover, comparing CO_2 and CH_4 emissions from different chamber-based experimental designs may result in a high variance sampled populations (Haddaway et al. 2014).

However, to accurately evaluate the effectiveness of the rewetting intervention on how much CO_2 emissions could be avoided due to rewetting intervention, it is better to compare carbon emissions at the same site (i.e., same vegetation cover, microtopography, and peat properties) from pair plots (controlled and treatment plots) using the chamber method. Comparing the carbon emissions from the drained and rewetted plots at the same site could minimize the co-effect of biophysical properties on the carbon fluxes. Therefore, this study conducts a meta-analysis based on individual studies that measured the carbon fluxes using the opaque chamber method from pair plots in the same site and measurement period. In addition, the time of carbon fluxes measurement after the rewetting intervention takes place should also be considered to assess the effectiveness of the rewetting intervention time by time.

The carbon fluxes measured by the opaque chamber method could be originated from the ecosystem respiration (Reco) or soil respiration (SRt) process (Oertel et al. 2016; Yang et al. 2019). In temperate and boreal climates, the peatlands are mainly covered with sedges, moss, and sphagnum, which may fit into the chamber headspace. Therefore, the CO_2 fluxes are reported primarily in the form of ecosystem respiration (Reco), the sum of soil respiration and autotrophic respiration by aboveground parts of plants. In contrast, in tropical forested peatlands, carbon fluxes measured by chamber method are mostly reported in soil respiration (SRt). In forested peatland, the chamber method cannot capture CO_2 fluxes from tree respiration but may capture CO_2 fluxes from roots and understorey vegetation respiration; therefore, reporting the CO_2 fluxes as soil respiration is preferable. For example, Jauhainen et al. (2008) and Lestari et al. (2022) reported carbon fluxes in tropical forested peatlands in the form of soil respiration (SRt). Meanwhile, many of their counterpart from temperate and boreal zones reported carbon fluxes in the form of ecosystem respiration (Haddaway et al. 2014). However, soil respiration usually accounts for the majority of ecosystem respiration; therefore, sometimes, soil respiration is described as an ecosystem respiration (Luo & Zhou 2006). Most of the studies conducted in temperate, boreal, and tropical use the opaque chamber method to measure CO_2 and CH_4 fluxes data from the peat surface. Therefore, they report the CO_2 fluxes in the form of soil or ecosystem respiration. This study used CO_2 fluxes reported either as soil or ecosystem respiration in the primary articles.

In contrast to a narrative review, a meta-analysis study could conduct a statistical and quantitative review of the effect of rewetting on carbon emissions. Meta-analysis studies have been used to summarize the statistical effects of interventions across multiple individuals (primary) studies and compare their consistency. In a meta-analysis, the effect of rewetting intervention from individual studies or the overall effect from reviewed studies is denoted by the effect size (Nakagawa & Santos 2012). In a meta-analysis, the magnitude and direction of the effect size caused by the intervention can be quantified precisely, which is essential in ecological and biological research to assess treatments during experimental studies (Nakagawa and Cuthill 2007; Reid 2006). However, to evaluate the effect size using meta-analysis, individual studies should have pair comparator plots, either a before-after control-impact (BACI) plot or a paired site, and an adequate sample size (Borenstein et al. 2009).

This study aimed to evaluate the effect of rewetting interventions in peatland ecosystems by comparing CO_2, CH_4 fluxes, and DOC from rewetted peatlands (treatment sites) with drained peatland ecosystems (control sites) in different climate zones at different restoration times, and to propose future field research directions.

2 Materials and methods

2.1 Data collection and search strategy

We collected all primary studies related to peat rewetting and CO_2 fluxes (from soil/ecosystem respiration), CH_4 fluxes, and DOC measurements between 1990 and 2018. Studies were found through websites and online databases, including the Directory of Open Access Journals (https://doaj.org), Google Scholar (https://scholar.google.com), and Scopus (https://www.scopus.com). The intervention keywords, terms, and strings used for website and database searches were “rewetted AND peat”; “restored AND peat,”; “rewetting AND peat”; and “restoration AND peat.” The terms “rewetting” and “rewetted” were used because the review was focused on rewetting interventions in drained peatlands. To locate other studies reporting on carbon fluxes from rewetted peatlands, but without “rewetted” or “rewetting” in their titles, we also used the terms “restoration” and “restored,” since rewetting constitutes only one facet of restoration interventions in drained peatlands. We conducted a second search to acquire articles published between 2019 and 2022. We only collected peer-reviewed articles written in English.

2.2 Study screening

All studies reporting experimental data regarding carbon emissions from rewetted peatlands or during rewetting interventions were of interest for this study. As such, we screened and assessed the relevance of identified studies through the following steps:

1. We first screened the titles of articles from websites and online databases, categorizing this literature into the intervention terms “rewetted,” “rewetting,” “restored,” and “restoration.” All reports and articles that did not include these terms were excluded.
2. We removed any duplicates (i.e., articles recorded more than once) in each category.
3. We read the abstracts and excluded from the database any articles that did not measure CO_2, CH_4, and DOC.
4. We then excluded all gray literature, non-experimental measurements, and review papers.
5. Articles remaining after step 4 were then marked as eligible for meta-analysis.
6. All eligible articles were assessed for quality, including the data presented in the Supplementary Material. All eligible studies had to have paired plots (measurement sites) for rewetted and comparator sites (drained sites) to calculate the rewetting effect size.

2.3 Data extraction

We then extracted the experimental data and other relevant data from the eligible studies, including the climate zone, date of rewetting, GWL data, peat nutrient status, land cover, and measurement methods, and input this data into an Excel spreadsheet. The resulting database was developed a priori based on previous literature reviews (Bussel et al. 2010). We only extracted carbon emissions data (soil/ecosystem respiration (CO_2), CH_4 fluxes, and DOC) from sites that had a comparator (i.e., that either had before-after plot data or used a pair-site approach), for example, comparing a rewetted with a drained hummock site or a rewetted with a drained hollow site, or comparing the same site before and after a rewetting intervention. We extracted the mean value, standard deviation (SD), and sample size (n) data from the eligible studies to calculate effect size. When studies reported only the standard error (SE) value, SE was converted into SD using the formula in Eq. (1) (Skinner et al. 2014), where SE is the standard error and n is the sample size:

$$SD = SE\sqrt{n} \tag{1}$$

If errors were not provided, SD values were calculated from the mean value and sample size or from the overall measurement data. The number of plots (measurement points) at each site was used as the true sample size (n) data rather than the number of repeated measurements in each plot. Therefore, sample size (n) was determined as the smallest number of plots. This approach results in a more conservative estimate of effect size (Bussel et al. 2010). We used Web Plot Digitizer™ to acquire data from charts (O. Abbasi et al. 2020) before pooling all data into Microsoft Excel™ as a raw database.

We classified cut-over, harvested, extracted, mined, drained, and abandoned peatland areas as drained (control) sites and rewetted areas as treatment sites. We also classified sites by year of rewetting, nutrient status (nutrient-poor or nutrient-rich), and climate zone (temperate, boreal, or tropical), according to the experimental site description reported in each study.

2.4 Effect size calculation

We used a random-effects meta-analysis to investigate the effect of rewetting on peatland ecosystem carbon fluxes. The magnitude of the rewetting effect size on carbon fluxes was evaluated using Hedges' *g* metric (bias-corrected standardized mean difference) (Borenstein et al. 2009). The Hedges' *g* effect size was calculated using the formula in Eq. (2):

$$g = d \times J \tag{2}$$

$$J = 1 - \left(\frac{3}{4 \times df - 1}\right) \tag{3}$$

$$d = \frac{\mu_1 - \mu_2}{\sigma} \tag{4}$$

where g is the Hedges' effect, d is the standard mean difference, J is the correction factor, df = n_{tot} (total sample size) – 2; μ_1 and μ_2 are mean values of rewetted and drained sites; and σ is pooled standard deviation. The value of σ was calculated using the formula in Eq. (4):

$$\sigma = \sqrt{\frac{(n_2 - 1)s_2^2 + (n_1 - 1)s_1^2}{n_1 + n_2 - 2}} \tag{5}$$

where n is the sample size and s^2 is a variance (Nakagawa & Cuthill 2007). In this study, Hedges' *g* was automatically calculated by inputting the means, standard deviations, and sample sizes of each study into Comprehensive Meta-Analysis (CMA™) software. According to Borenstein et al. (2009), a Hedges' *g* value of 0.2 or less is considered a small effect size, a value of around 0.5 is medium, and a value around 0.8 or above is large (Nakagawa et al. 2017). In addition to Hedges' *g* metric, we also used raw mean difference (D) to estimate any increase or decrease in carbon fluxes following rewetting. Hedges' *g* metric is unitless (and shows the magnitude of effect size), while the metric unit of D is g m^{-2}

day^{-1} for CO_2 and CH_4 and g L $^{-1}$ for DOC concentration. We, therefore, used the D metric to estimate the actual difference in carbon fluxes between rewetted and drained sites. A positive effect size indicates that a rewetting intervention leads to higher carbon emissions (increasing effect), whereas a negative effect size indicates that a rewetting intervention leads to lower carbon emissions (decreasing effect).

Heterogeneity, which is defined as variation or dispersion of effect size from study to study, was assessed using Higgins' I^2 statistic. I^2 can also be defined as a measure of inconsistency in effect size across studies (Borenstein et al. 2009; Reid 2006). Heterogeneity was considered to be low, medium, and high with I^2 values of around 25, 50, and 75%, respectively (Nakagawa et al. 2017; Reid 2006). Subgroup analysis was performed when I^2 was greater than 0.25 based on available data; in this study case, we used climate zone and year of monitoring after rewetting as moderators. We report publication bias using a funnel plot chart.

3 Results

3.1 Primary data availability

This review examined the effect size of rewetting interventions on previously drained peatlands. We included primary studies reporting soil/ecosystem respiration (CO_2), CH_4 fluxes, and DOC concentration at rewetted sites and (counterpart) drained sites. A total of 2089 records were identified from online databases. After removing duplicates and screening titles and abstracts, 393 records met our criteria for further review, which involved reading the full text. From this number, we excluded a further 366 articles because (i) the article was not relevant to rewetting interventions; (ii) the article was a review article without primary field data; (iii) the article discussed laboratory work without field measurements; (iv) the article focused on modeling work; or (v) the article did not have a comparator site or plots. By the end of this review, we found just 28 primary studies with comparator sites in their experimental design (comparing rewetted with drained). Steps and results from the identification and screening processes are shown in Fig. 1.

From January to April 2021, we undertook a second search and screening process to retrieve recent studies published after 2019. The articles identified in this search were screened using the same methods described in Section 2.3; seven primary studies published after 2019 were added to the meta-analysis. The list of individual studies used to calculate effect size is available in Supplementary Information Table S1.

The geographical distribution of primary studies was unbalanced, with a focus mainly on temperate climate zones and just a few primary studies conducted in tropical climate zones (Table 1). Climate zone data were taken from the site description section of each study. In terms of the time when monitoring took place after rewetting, CO_2 and CH_4 emissions were usually measured at some point within the first three years after the initial rewetting intervention took place (Table 1). Just a few studies monitored CO_2 and CH_4 emissions consecutively over the first three years after rewetting (Renou-Wilson et al. 2016, 2018; Waddington et al. 2010; Waddington & Day 2007). Primary studies that measured carbon emissions in the 6th, 10th, and 30th year after rewetting (Gatis et al. 2020; Strack & Zuback 2013; Vanselow-Algan et al. 2015; Vybornova et al. 2019) were placed under the $\geq$5-year label (Table 1) due to the small number of studies and data observations available.

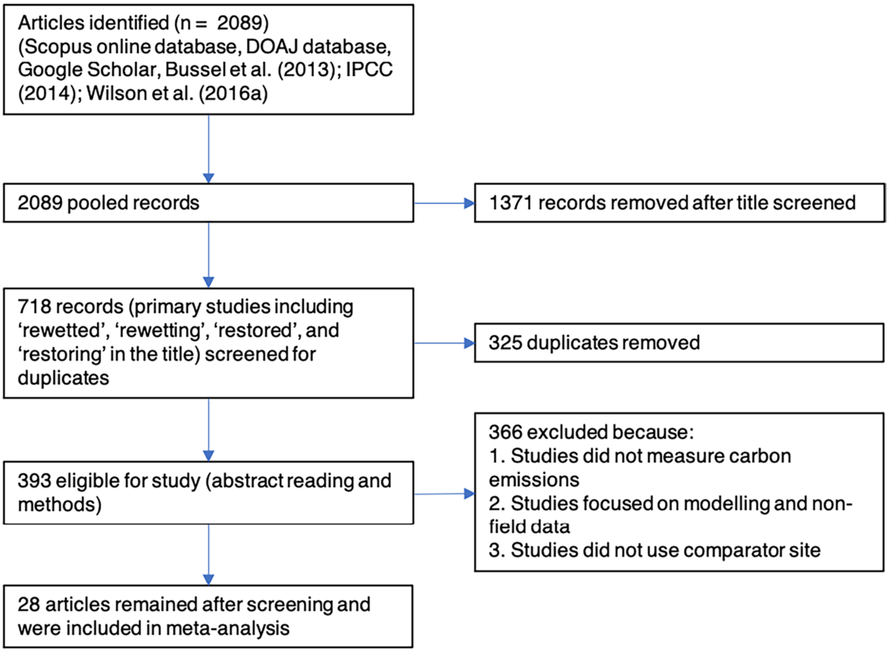


Fig. 1 Flowchart of article screening process

Table 1 Distribution of primary studies by climate zone (above) and year of monitoring after rewetting (below). Numbers indicate primary studies and numbers in brackets reflect observation data used to calculate effect size

Outcome	Boreal	Temperate	Tropical		Total
CO_2	2 (6)	12 (33)	3 (9)		17 (48)
CH_4	3 (18)	13 (44)	2 (5)		18 (67)
DOC	2 (2)	3 (3)	0		5 (5)
Outcome	Year when carbon emissions were monitored (after rewetting)				
	1st	2nd	3rd	4th	≥5th
CO2	21	8	4	5	8
CH4	26	17	7	6	9
DOC	5	0	0	0	0

In terms of experimental design, 48 effect sizes for CO_2 emissions were taken from 17 studies, and of these, before-after plots were used for 24 effect sizes (6 studies); the remaining 24 effect sizes came from 10 studies that used paired-site comparison plots. In terms of effect size for CH_4 emissions, 67 effect sizes were taken from 18 studies, 35 of which used before-after plots, with the remaining 32 based on paired sites. All studies used the opaque chamber method to observe CO_2 and CH_4 fluxes at the study sites.

3.2 Effect of rewetting on CO_2 and CH_4 emissions

Based on all observed data (n = 48), rates for CO_2 emissions from rewetted peatlands ranged between 0.57 and 43.51 g CO_2 m^{-2} day^{-1}, with a mean rate of 10.16 ± 1.20 g CO_2 m^{-2} day^{-1} across all studies. For CO_2 emissions from drained peatlands, rates ranged between 1.39 and 41.96 g CO_2 m^{-2} day^{-1}, with a mean rate of 12.04 ± 1.40 g CO_2 m^{-2} day^{-1} across all studies (Fig. 2). One-way ANOVA showed that rewetted peatlands had lower CO_2 emission rates than drained peatlands, with a p-value of 0.3.

In comparison, the meta-analysis results show that the overall random effect size generated from the all-observation dataset was g = −0.616 (95% CI −0.947 to −0.284) (Fig. 3). This Hedges' g effect size was considered a large effect size. When the Hedges' g value is converted into raw mean difference (D), the rewetting intervention shows reduced CO_2 emissions by an average of −1.43 ± 0.36 g CO_2 m^{-2} day^{-1}, with a reduction range of −0.73 to −2.14 g CO_2 m^{-2} day^{-1}. Nevertheless, the heterogeneity value was I^2 = 84.51%, which was considered high but still under the average I^2 value of other ecological meta-analysis studies (92%) (Nakagawa et al. 2017). Subgroup analysis was therefore required. Effect size based on climate zone (subgroup analysis) showed that temperate zones had the highest effect size with g = −0.798 (95% CI; −1.246 to −0.350), followed by tropical climate zones with g = −0.338 (95% CI; −0.867 to 0.190), and boreal climate zones with g = −0.209 (95% CI; −0.938 to 0.520); only in temperate zones was the effect size significant (effect size did not cross zero and p-value < 0.001) (Fig. 5). In terms of raw mean difference (D), rewetting interventions reduced CO_2 emissions by approximately −1.407 ± 0.394, −1.163 ± 1.312, and −2.509 ± 1.378 g m^{-2} day^{-1}, respectively, for boreal, temperate, and tropical zones. Although the meta-analysis was conducted in subgroups (climate zone and monitoring year), heterogeneity values were still high, with I^2 between 70 and 88%.

Regarding CH_4 emissions, the rates from rewetted peatlands ranged between −0.052 and 0.52 g CH_4 m^{-2} day^{-1}, with a mean rate of 0.068 ± 0.014 g CH_4 m^{-2} day^{-1} across all observed data (n = 67). Meanwhile, CH_4 emission rates in drained peatlands ranged

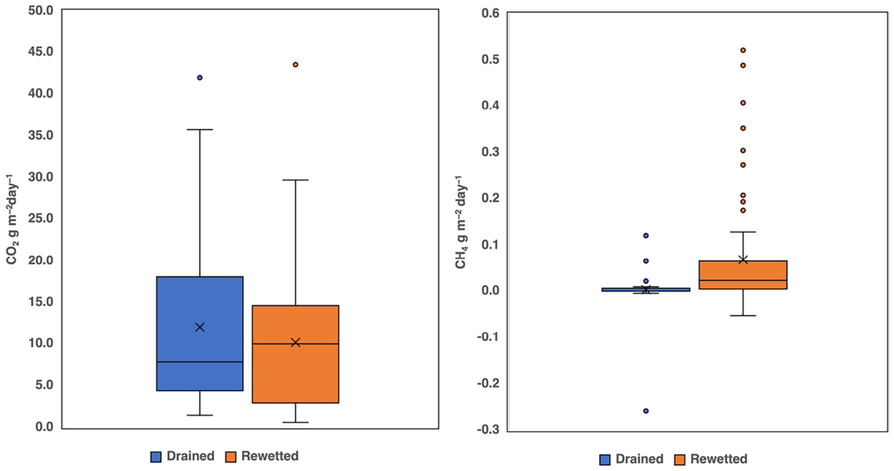
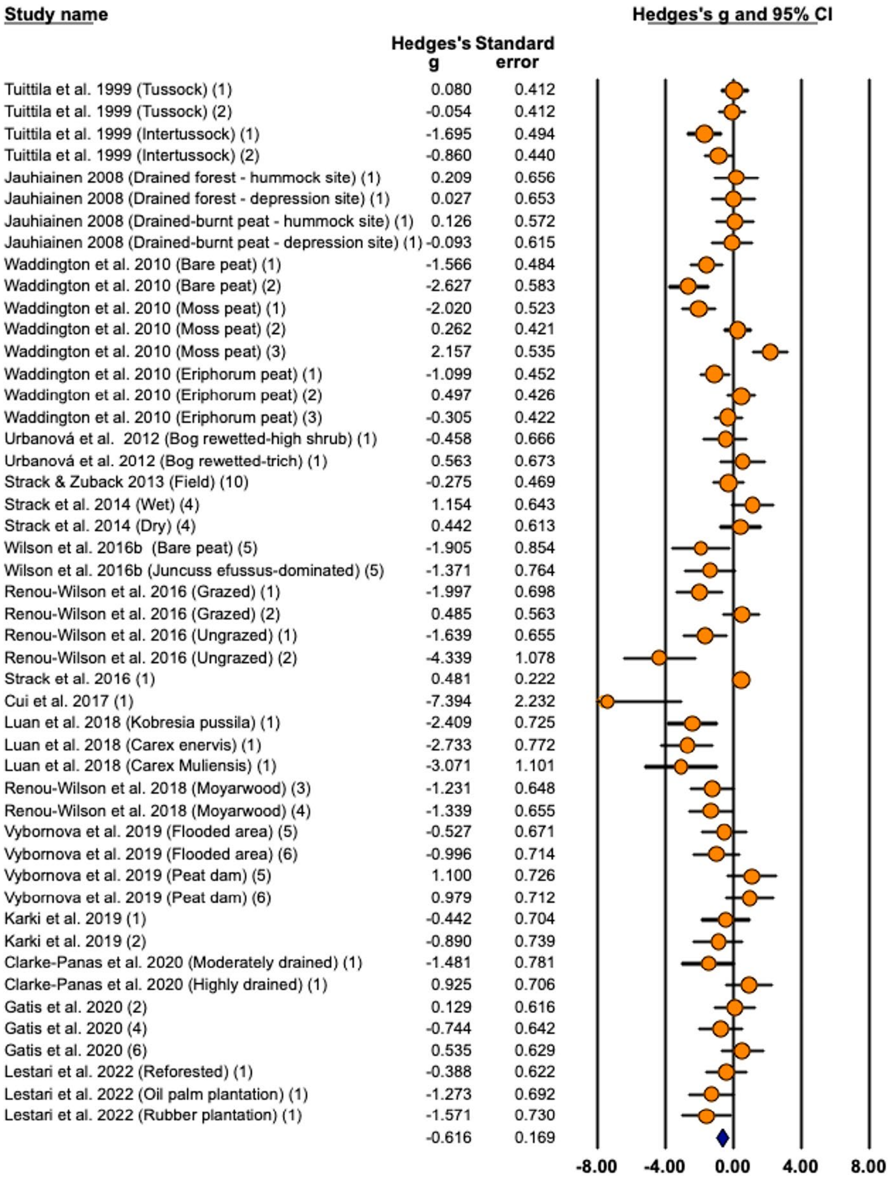


Fig. 2 Boxplot of CO_2 emissions (n = 48) and CH_4 emissions (n = 67) in drained and rewetted sites based on all observation datasets (all climate zones and monitoring years) used in meta-analysis. Box plots show mean (cross), median (solid line), and outliers (solid dots)



Study name	Hedges's g	Standard error
Tuittila et al. 1999 (Tussock) (1)	0.080	0.412
Tuittila et al. 1999 (Tussock) (2)	-0.054	0.412
Tuittila et al. 1999 (Intertussock) (1)	-1.695	0.494
Tuittila et al. 1999 (Intertussock) (2)	-0.860	0.440
Jauhiainen 2008 (Drained forest - hummock site) (1)	0.209	0.656
Jauhiainen 2008 (Drained forest - depression site) (1)	0.027	0.653
Jauhiainen 2008 (Drained-burnt peat - hummock site) (1)	0.126	0.572
Jauhiainen 2008 (Drained-burnt peat - depression site) (1)	-0.093	0.615
Waddington et al. 2010 (Bare peat) (1)	-1.566	0.484
Waddington et al. 2010 (Bare peat) (2)	-2.627	0.583
Waddington et al. 2010 (Moss peat) (1)	-2.020	0.523
Waddington et al. 2010 (Moss peat) (2)	0.262	0.421
Waddington et al. 2010 (Moss peat) (3)	2.157	0.535
Waddington et al. 2010 (Eriphorum peat) (1)	-1.099	0.452
Waddington et al. 2010 (Eriphorum peat) (2)	0.497	0.426
Waddington et al. 2010 (Eriphorum peat) (3)	-0.305	0.422
Urbanová et al. 2012 (Bog rewetted-high shrub) (1)	-0.458	0.666
Urbanová et al. 2012 (Bog rewetted-trich) (1)	0.563	0.673
Strack & Zuback 2013 (Field) (10)	-0.275	0.469
Strack et al. 2014 (Wet) (4)	1.154	0.643
Strack et al. 2014 (Dry) (4)	0.442	0.613
Wilson et al. 2016b (Bare peat) (5)	-1.905	0.854
Wilson et al. 2016b (Juncuss efussus-dominated) (5)	-1.371	0.764
Renou-Wilson et al. 2016 (Grazed) (1)	-1.997	0.698
Renou-Wilson et al. 2016 (Grazed) (2)	0.485	0.563
Renou-Wilson et al. 2016 (Ungrazed) (1)	-1.639	0.655
Renou-Wilson et al. 2016 (Ungrazed) (2)	-4.339	1.078
Strack et al. 2016 (1)	0.481	0.222
Cui et al. 2017 (1)	-7.394	2.232
Luan et al. 2018 (Kobresia pussila) (1)	-2.409	0.725
Luan et al. 2018 (Carex enervis) (1)	-2.733	0.772
Luan et al. 2018 (Carex Muliensis) (1)	-3.071	1.101
Renou-Wilson et al. 2018 (Moyarwood) (3)	-1.231	0.648
Renou-Wilson et al. 2018 (Moyarwood) (4)	-1.339	0.655
Vybornova et al. 2019 (Flooded area) (5)	-0.527	0.671
Vybornova et al. 2019 (Flooded area) (6)	-0.996	0.714
Vybornova et al. 2019 (Peat dam) (5)	1.100	0.726
Vybornova et al. 2019 (Peat dam) (6)	0.979	0.712
Karki et al. 2019 (1)	-0.442	0.704
Karki et al. 2019 (2)	-0.890	0.739
Clarke-Panas et al. 2020 (Moderately drained) (1)	-1.481	0.781
Clarke-Panas et al. 2020 (Highly drained) (1)	0.925	0.706
Gatis et al. 2020 (2)	0.129	0.616
Gatis et al. 2020 (4)	-0.744	0.642
Gatis et al. 2020 (6)	0.535	0.629
Lestari et al. 2022 (Reforested) (1)	-0.388	0.622
Lestari et al. 2022 (Oil palm plantation) (1)	-1.273	0.692
Lestari et al. 2022 (Rubber plantation) (1)	-1.571	0.730
	-0.616	0.169

Fig. 3 Analysis of CO_2 emissions. Effect size is in Hedges' *g*. CI, confidence interval. Negative values indicate lower CO_2 emissions and positive values indicate higher CO_2 emissions into the atmosphere. Rewetting peatlands caused reduced CO_2 emissions with an overall effect size (blue diamond) of −0.616 ± 0.169. Number in brackets after study name indicates year monitoring took place after rewetting intervention

between −0.26 and 0.12 g CH_4 m^{-2} day^{-1}, with a mean rate of 0.0034 ± 0.005 g CH_4 m^{-2} day^{-1} across all datasets. These differences highlight that rewetted sites had significantly higher CH_4 emissions than drained sites, with a p-value of <0.001 by one-way ANOVA.

The meta-analysis showed an overall effect size of rewetting interventions in terms of CH_4 emissions of g =0.891 (95% CI 0.674 to 1.108) (Fig. 4). This positive effect size was considered a large effect size. Converting Hedges' g to a D effect size metric indicated that rewetting drained peatlands could increase CH_4 emissions by an average of 0.012 ± 0.001 g CH_4 m^{-2} day^{-1} (95% CI 0.009 to 0.014). The heterogeneity of the rewetting effect size on CH_4 emissions was around I^2 = 50.41%, which was considered medium. Subgroup analysis based on climate zone indicated that the overall random effect size in terms of CH_4 emissions was highest in temperate climate zones, followed by boreal and tropical climate zones, with Hedges' g of 1.108 ± 0.144, 0.805 ± 0.183, and 0.096 ± 0.284, respectively (Fig. 5). Converting Hedges' g to D indicates that rewetting increased CH_4 emissions by approximately 0.018 ± 0.002, 0.009 ± 0.002, and −0.001 ± 0.001g m^{-2} day^{-1} in temperate, boreal, and tropical climate zones, respectively. Subgroup analysis based on climate zone and monitoring year showed slightly reduced effect size heterogeneity.

Looking at the year when monitoring took place, an opposite trend was found between the effect of rewetting on CH_4 emissions and CO_2 emissions. The rewetting effect size in terms of CH_4 emissions showed an increasing trend over time ($r^2 = 0.853$, p-value > 0.05), whereas the rewetting effect size in terms of CO_2 emissions remained unchanged from that seen in the first to fourth years after rewetting ($r^2 = 0.02$, p-value > 0.05) (Fig. 6).

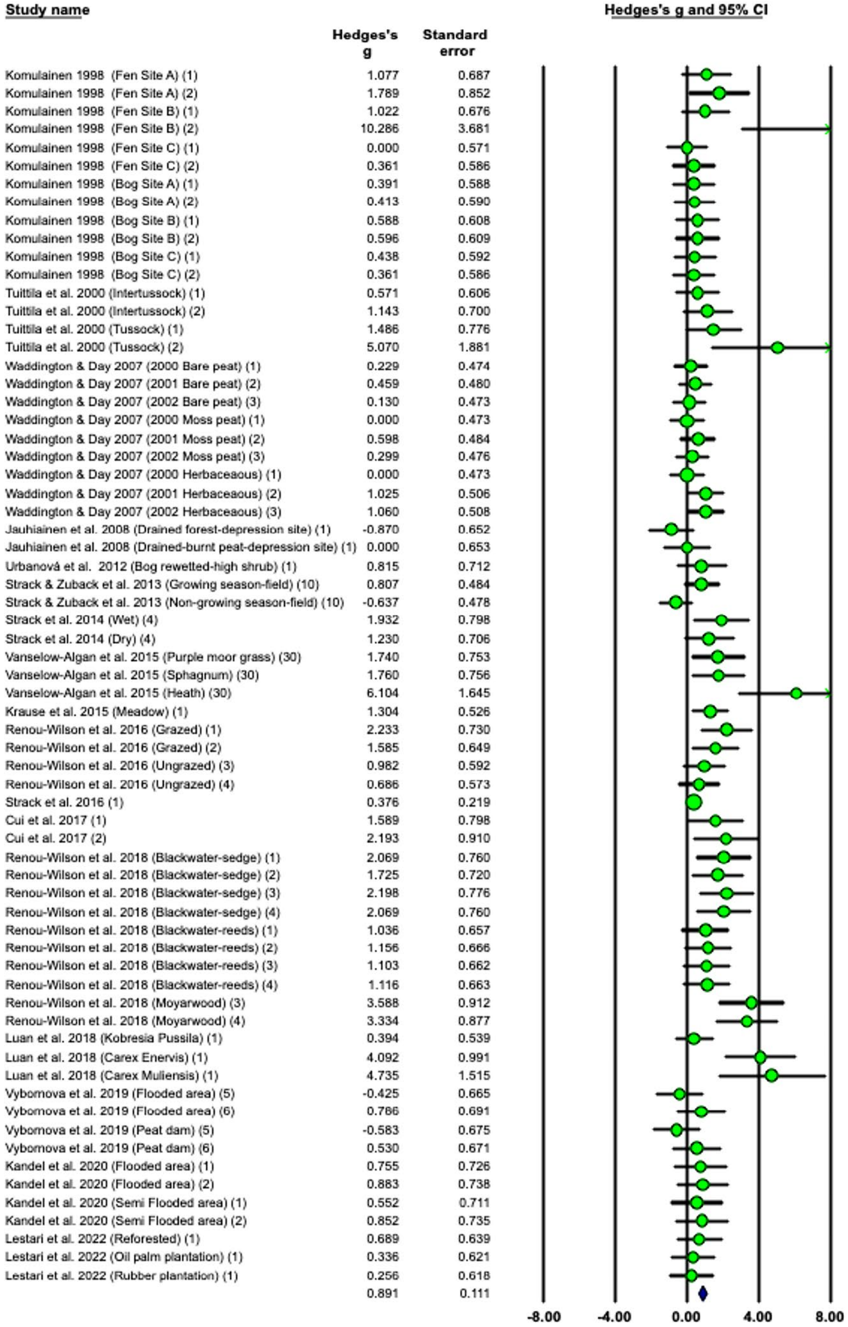
3.3 Effect of rewetting on DOC concentration

Like gaseous emissions, the loss of peatland carbon stocks to waterways through pore water is another important factor. However, without data on the quantity and direction of water flows in drained and rewetted peatlands, it is hard to estimate the actual rates of carbon lost through leaching. Only one of the reviewed primary studies measured waterborne carbon flux from peatland catchment areas, and had adequate supporting data, including a sample size of more than one. Conversely, we identified five studies that provide comparisons of DOC concentration data in rewetted and drained peatlands with measurements from more than one site. For that reason, we performed a meta-analysis of the effect of rewetting on DOC concentration (see Fig. 7 for the forest plot analysis). All studies took water samples from the peat (pore water) and were conducted in temperate peatlands. As Fig. 7 shows, the overall random effect size of rewetting was not significantly different from zero, with g value = 0.191 (95% CI −0.668 to 1.124); converted to raw mean difference, the rewetting increased by around 7.8 ± 9.5 gram/L.

4 Discussion

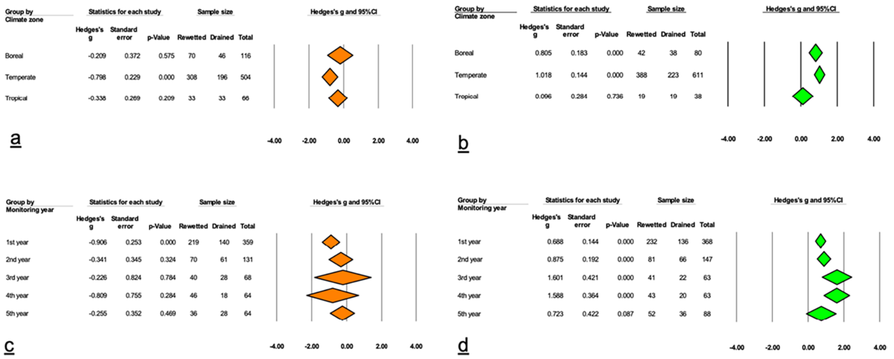
4.1 The effect of rewetting interventions on CO_2, CH_4 emissions, and DOC

According to the meta-analysis, rewetting has an overall negative effect on CO_2 emissions but an overall positive effect on CH_4 emissions. These overall effects were considered large effect sizes and significant, since the 95% confident interval does not cross the zero line (Figs. 3 and 4). These findings agree with previous review studies reporting a decreasing trend for CO_2, and an increasing trend for CH_4 when the GWL increases closer to the peat surface (Jauhiainen et al. 2016; Zhong et al. 2020). Similar overall rewetting effect sizes in terms of CH_4 and CO_2 emissions were also reported by Bussel et al. (2010) in their review study. Taking a broader view, the meta-analysis shows that wetter peatlands tend to induce



Study name	Hedges's g	Standard error
Komulainen 1998 (Fen Site A) (1)	1.077	0.687
Komulainen 1998 (Fen Site A) (2)	1.789	0.852
Komulainen 1998 (Fen Site B) (1)	1.022	0.676
Komulainen 1998 (Fen Site B) (2)	10.286	3.681
Komulainen 1998 (Fen Site C) (1)	0.000	0.571
Komulainen 1998 (Fen Site C) (2)	0.361	0.586
Komulainen 1998 (Bog Site A) (1)	0.391	0.588
Komulainen 1998 (Bog Site A) (2)	0.413	0.590
Komulainen 1998 (Bog Site B) (1)	0.588	0.608
Komulainen 1998 (Bog Site B) (2)	0.596	0.609
Komulainen 1998 (Bog Site C) (1)	0.438	0.592
Komulainen 1998 (Bog Site C) (2)	0.361	0.586
Tuittila et al. 2000 (Intertussock) (1)	0.571	0.606
Tuittila et al. 2000 (Intertussock) (2)	1.143	0.700
Tuittila et al. 2000 (Tussock) (1)	1.486	0.776
Tuittila et al. 2000 (Tussock) (2)	5.070	1.881
Waddington & Day 2007 (2000 Bare peat) (1)	0.229	0.474
Waddington & Day 2007 (2001 Bare peat) (2)	0.459	0.480
Waddington & Day 2007 (2002 Bare peat) (3)	0.130	0.473
Waddington & Day 2007 (2000 Moss peat) (1)	0.000	0.473
Waddington & Day 2007 (2001 Moss peat) (2)	0.598	0.484
Waddington & Day 2007 (2002 Moss peat) (3)	0.299	0.476
Waddington & Day 2007 (2000 Herbaceaous) (1)	0.000	0.473
Waddington & Day 2007 (2001 Herbaceaous) (2)	1.025	0.506
Waddington & Day 2007 (2002 Herbaceaous) (3)	1.060	0.508
Jauhiainen et al. 2008 (Drained forest-depression site) (1)	-0.870	0.652
Jauhiainen et al. 2008 (Drained-burnt peat-depression site) (1)	0.000	0.653
Urbanová et al. 2012 (Bog rewetted-high shrub) (1)	0.815	0.712
Strack & Zuback et al. 2013 (Growing season-field) (10)	0.807	0.484
Strack & Zuback et al. 2013 (Non-growing season-field) (10)	-0.637	0.478
Strack et al. 2014 (Wet) (4)	1.932	0.798
Strack et al. 2014 (Dry) (4)	1.230	0.706
Vanselow-Algan et al. 2015 (Purple moor grass) (30)	1.740	0.753
Vanselow-Algan et al. 2015 (Sphagnum) (30)	1.760	0.756
Vanselow-Algan et al. 2015 (Heath) (30)	6.104	1.645
Krause et al. 2015 (Meadow) (1)	1.304	0.526
Renou-Wilson et al. 2016 (Grazed) (1)	2.233	0.730
Renou-Wilson et al. 2016 (Grazed) (2)	1.585	0.649
Renou-Wilson et al. 2016 (Ungrazed) (3)	0.982	0.592
Renou-Wilson et al. 2016 (Ungrazed) (4)	0.686	0.573
Strack et al. 2016 (1)	0.376	0.219
Cui et al. 2017 (1)	1.589	0.798
Cui et al. 2017 (2)	2.193	0.910
Renou-Wilson et al. 2018 (Blackwater-sedge) (1)	2.069	0.760
Renou-Wilson et al. 2018 (Blackwater-sedge) (2)	1.725	0.720
Renou-Wilson et al. 2018 (Blackwater-sedge) (3)	2.198	0.776
Renou-Wilson et al. 2018 (Blackwater-sedge) (4)	2.069	0.760
Renou-Wilson et al. 2018 (Blackwater-reeds) (1)	1.036	0.657
Renou-Wilson et al. 2018 (Blackwater-reeds) (2)	1.156	0.666
Renou-Wilson et al. 2018 (Blackwater-reeds) (3)	1.103	0.662
Renou-Wilson et al. 2018 (Blackwater-reeds) (4)	1.116	0.663
Renou-Wilson et al. 2018 (Moyarwood) (3)	3.588	0.912
Renou-Wilson et al. 2018 (Moyarwood) (4)	3.334	0.877
Luan et al. 2018 (Kobresia Pussila) (1)	0.394	0.539
Luan et al. 2018 (Carex Enervis) (1)	4.092	0.991
Luan et al. 2018 (Carex Muliensis) (1)	4.735	1.515
Vybornova et al. 2019 (Flooded area) (5)	-0.425	0.665
Vybornova et al. 2019 (Flooded area) (6)	0.786	0.691
Vybornova et al. 2019 (Peat dam) (5)	-0.583	0.675
Vybornova et al. 2019 (Peat dam) (6)	0.530	0.671
Kandel et al. 2020 (Flooded area) (1)	0.755	0.726
Kandel et al. 2020 (Flooded area) (2)	0.883	0.738
Kandel et al. 2020 (Semi Flooded area) (1)	0.552	0.711
Kandel et al. 2020 (Semi Flooded area) (2)	0.852	0.735
Lestari et al. 2022 (Reforested) (1)	0.689	0.639
Lestari et al. 2022 (Oil palm plantation) (1)	0.336	0.621
Lestari et al. 2022 (Rubber plantation) (1)	0.256	0.618
	0.891	0.111

Fig. 4 Analysis of effect sizes comparing rewetted and drained peatlands by CH_4 emissions. Effect size is in Hedges' *g*. CI, confidence interval. Positive value indicates more emissions from rewetted peatland than drained peatland, and vice versa. Overall effect size (blue diamond) is 0.891 ± 0.111. Number in brackets after study name indicates year monitoring took place after rewetting intervention



a

Group by Climate zone	Statistics for each study			Sample size		
	Hedges's g	Standard error	p-Value	Rewetted	Drained	Total
Boreal	-0.209	0.372	0.575	70	46	116
Temperate	-0.798	0.229	0.000	308	196	504
Tropical	-0.338	0.269	0.209	33	33	66

b

Group by Climate zone	Statistics for each study			Sample size		
	Hedges's g	Standard error	p-Value	Rewetted	Drained	Total
Boreal	0.805	0.183	0.000	42	38	80
Temperate	1.018	0.144	0.000	388	223	611
Tropical	0.096	0.284	0.736	19	19	38

c

Group by Monitoring year	Statistics for each study			Sample size		
	Hedges's g	Standard error	p-Value	Rewetted	Drained	Total
1st year	-0.906	0.253	0.000	219	140	359
2nd year	-0.341	0.345	0.324	70	61	131
3rd year	-0.226	0.824	0.784	40	28	68
4th year	-0.809	0.755	0.284	46	18	64
5th year	-0.255	0.352	0.469	36	28	64

d

Group by Monitoring year	Statistics for each study			Sample size		
	Hedges's g	Standard error	p-Value	Rewetted	Drained	Total
1st year	0.688	0.144	0.000	232	136	368
2nd year	0.875	0.192	0.000	81	66	147
3rd year	1.601	0.421	0.000	41	22	63
4th year	1.588	0.364	0.000	43	20	63
5th year	0.723	0.422	0.087	52	36	88

Fig. 5 Subgroup analysis based on **a**, **b** climate zone (CO_2 and CH_4) and **c**, **d** year monitoring took place after rewetting (CO_2 and CH_4). Effect size is in Hedges' *g* with 95% confidence interval (CI). Positive and negative values under Hedges' *g* indicate increasing and decreasing CH_4 and CO_2 emissions. Sample size is number of samples from studies used to calculate effect size

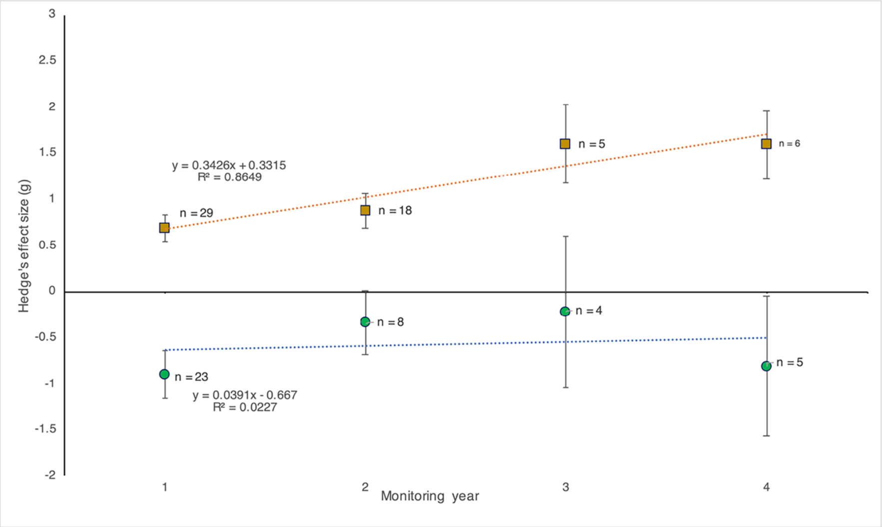
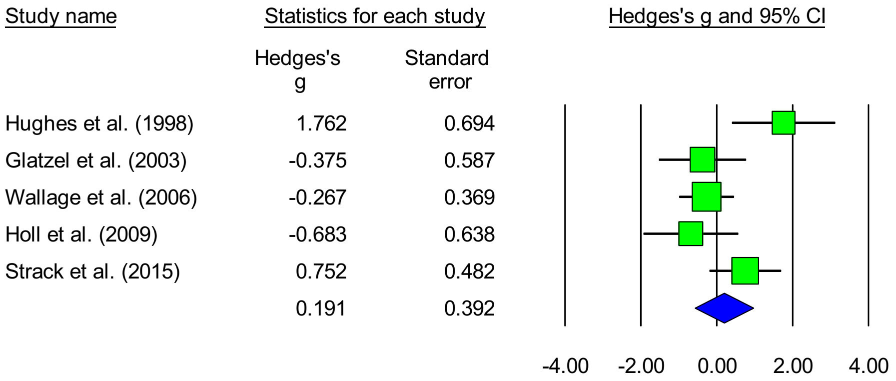


Fig. 6 Effect size (Hedges' *g*) based on year monitoring took place after rewetting. Solid squares and circles indicate effect sizes in terms of CH_4 and CO_2 emissions, respectively. Error bars are standard error (SE) and (*n*) is the number of individual effect sizes. Positive and negative values of Hedges' *g* indicate increasing and decreasing CH_4 and CO_2 emissions after rewetting interventions, respectively

a reduction in CO_2 emissions, but an increase in CH_4 emissions (Haddaway et al. 2014). In other words, the rewetting intervention of drained peatlands can avoid a certain amount of CO_2 gas concentration released into the atmosphere. For example, rewetting intervention could reduce the net emissions up to 15.41 Mg CO_2-eq ha^{-1} year^{-1} (25%) in reforested, 18.36 Mg CO_2-eq ha^{-1} year^{-1} (18%) in oil palm, and 28.87 Mg CO_2-eq ha^{-1} year^{-1} (17%) in rubber plantation areas (Lestari et al. 2022). In contrast, for the meta-analysis, it could be inferred that the drier the peatlands tend to increase the CO_2 emissions. For example, Hergoualc'h and Verchot (2012) found that converting pristine peat swamp forests to other



Study name	Hedges's g	Standard error
Hughes et al. (1998)	1.762	0.694
Glatzel et al. (2003)	-0.375	0.587
Wallage et al. (2006)	-0.267	0.369
Holl et al. (2009)	-0.683	0.638
Strack et al. (2015)	0.752	0.482
	0.191	0.392

Fig. 7 Forest-plot analysis of dissolved organic carbon (DOC) concentration. Hedges' *g* indicates effect size. CI, confidence interval. Negative values indicate smaller DOC concentration and positive values indicate greater DOC concentration in pore water. Blue diamond indicates random overall effect size of rewetting (0.191 ± 0.392)

land uses, e.g., cropland, drained forest, or oil palm plantation, resulted in a negative effect size in terms of CH_4 emissions (Hedges' $g = -0.4 \pm 0.2$) and a positive effect size in CO_2 emissions (Hedges' $g = 0.3 \pm 0.4$). The conversion of pristine peat swamp forest to other land uses associated with drainage lowered the GWL and increased the aerobic zone (Page et al. 2009), which is what causes the negative effect size to CH_4 emissions and positive effect size to the CO_2 emissions.

The forest plots (see Figs. 3, 4, and 7) highlight a few effect sizes that were inconsistent with the overall effect sizes; indeed, a few are the opposite of the overall effect size. Twelve individual effect sizes in terms of CO_2 emissions were positive following rewetting interventions (Fig. 3), although only one was significant (Waddington et al. 2010). The positive effect size (indicating higher CO_2 emissions in rewetted peatland than in drained peatland) could be the result of increased plant production and fresh organic matter from litter, and in several cases, after a long drought, the rewetting intervention removes moisture stress in the rewetted site which increased organic matter decomposition (Zhong et al. 2020). Another possibility is that the GWL in the rewetted peatland was still under the peat surface (e.g., −30 cm below the surface), which creates the perfect conditions for soil microbes to be more active. In very dry conditions, the soil moisture content is low because of very deep GWL (e.g., −100 cm below the peat surface); in this condition, the ecosystem respiration (CO_2 emissions) will be low. Rewetting the dry peat would raise the GWL and eventually increase the soil moisture content to an intermediate level (near the field capacity), which provides optimum conditions for the ecosystem respiration (Luo & Zhou 2006). In their meta-analysis study, Haddaway et al. (2014) reported a non-significant positive effect size in terms of CO_2 emissions (greater CO_2 emissions in restored than in unrestored sites), albeit only based on three primary studies (three effect sizes).

In contrast, from 67 individual rewetting effect sizes in terms of CH_4 emissions, only four individual effect sizes were negative (Jauhiainen et al. 2008; Strack & Zuback 2013; Vybornova et al. 2019) or inconsistent in the forest plot (Fig. 4). None of these were significant. The relatively lower CH_4 emissions in rewetted peatlands could be due to a lower supply of high-quality (easy to decompose) organic material on peat surfaces and higher CH_4 oxidation by methanotrophic bacteria in the oxic layer than CH_4 production. Another possible explanation is that the CH_4 gas formed under rewetted conditions could not diffuse to the atmosphere before monitoring occurred (Jauhiainen et al. 2008). There were also relatively higher positive effect sizes (Fig. 4), mainly in the plot covered by plants rich in aerenchymous tissue in their root systems. The aerenchyma directly enables CH4 transport from the peat layer to the atmosphere, bypassing the aerobic zone and avoiding CH_4 oxidation. These plant species were named "shunt" species by Couwenberg (2009). Shunt species such as *Carex*, *Eriophorum, Calla*, and *Cladium* provide a transport system through aerenchyma and new labile substrates to be used by methanogens (Whalen 2005). This could explain the variation of CH_4 emissions by approximately 25–97% (Couwenberg 2009). A recent article that measured the CH_4 emissions from drained and rewetted tropical peatlands has shown a significant increase in CH_4 emissions (15- to 80-fold) after rewetting intervention (Lestari et al. 2022)

Regarding DOC, five studies provided five individual effect sizes in terms of DOC concentration in peat water. We used the total value of DOC concentration reported in each study rather than the DOC concentration found at different sampling depths. This result indicates that rewetting had no effect or an uncertain effect on DOC concentration (Fig. 7). An insignificant effect size in terms of DOC was also reported by Haddaway et al. (2014). However, three of five individual effect sizes showed that rewetting could reduce DOC concentration. Strack et al. (2015) described increased DOC concentration in rewetted conditions due to plant productivity following restoration. In contrast, Höll et al. (2009) argued that the decreased DOC concentration following restoration was due to the lower rate of peat decomposition in rewetted conditions. Overall, these results suggest that rewetting seems to have uncertain effects on DOC concentration, given the varied effect sizes in the studies, which were not considered significant.

A few studies, however, highlighted the inconsistencies in rewetting effect sizes when looking at all climate zones and monitoring years (Figs. 3, 4, and 7). Such inconsistencies also contribute to the heterogeneity of the effect sizes. The inconsistency and heterogeneity suggest that other factors influence the effect size of rewetting interventions, such as the presence of vegetation cover at the study site. For example, based on effect sizes derived from Waddington et al. (2010), the rewetting intervention has a larger reducing effect on CO_2 emissions in bare peat than in vegetated peat, as shown in forest plots (Fig. 3). This could be because in bare peat, when the condition is waterlogged, the oxygen availability decreases rapidly, and diffusion of oxygen to the peat layer is limited due to a lack of media transport, e.g., roots or vascular plants (Girkin et al. 2018). On the other hand, in vegetated peat, for example, peat covered with *Eriophorum vaginatum* may still emit CO_2 emissions even in rewetted conditions because of oxygen transfer via the aerenchyma or root system (Jordan et al. 2016). In contrast, a larger increasing effect of CH_4 emissions was shown in vegetated peat than in bare peat, as shown in the forest plot (Fig. 4). This demonstrates that GWL coupled with vegetation, especially aerenchymous species, firmly controls CO_2 and CH_4 emissions (Jordan et al. 2016). A change in vegetation cover between the time of rewetting and the time of monitoring could also affect the rewetting effect size (e.g., see effect sizes derived from Renou-Wilson et al. (2016a, b) in Figs. 3 and 4). In addition, GWL changes before and after rewetting of previously drained peatland can affect the magnitude of the effect size (Figure S1); likewise, if a rewetted site has different annual GWL averages from one year to the next, this can also affect the magnitude of the effect size.

Our finding shows that rewetting intervention has a reducing effect on or avoids CO_2 emissions of around -1.43 ± 0.36 g CO_2 m^{-2} day^{-1} or -1.42 ± 0.35 Mg CO_2-C ha^{-1} $year^{-1}$, and an increasing effect on CH_4 emissions of around 0.012 ± 0.001 g CH_4 m^{-2}

day^{-1} or 0.033 ± 0.003 Mg CH_4-C ha^{-1} year^{-1}. However, those effects were still uncertain and could be improved if more carbon fluxes data from primary studies were collected and included in the meta-analysis. From all primary articles used in this meta-analysis study, the CO_2 fluxes were measured using the opaque chamber installed on the peat surface, which only gives information about the total soil respiration, not the net ecosystem exchange (NEE), the net CO_2 flux from the ecosystem to the atmosphere. Moreover, from the primary articles used in this meta-analysis, only one study measured heterotrophic respiration (Rh) using trenching method from peatland (Lestari et al. 2022). R_h value is a significant parameter for rewetting intervention since carbon fluxes from R_h are a major component of the carbon loss from the peat (Hergoualc'h et al., 2017). Furthermore, data on other non-CO_2 fluxes such as carbon monoxide (CO), DOC, DIC, and volatile organic compounds (VOCs) were not available, which also contributes to the total carbon fluxes from the peat soil (Chapin et al. 2006; Randerson et al. 2002).

4.2 Effect size and rewetting time

Environmental changes in the peatlands from being drained to being rewetted affect biogeochemical processes. The effect of rewetting on these biogeochemical processes varies, depending on the peatland type and the period since rewetting intervention took place. Vybornova et al. (2019), for example, reported a disturbance effect in the first year of measurement, as well as newly dead organic matter; this disturbance led to higher carbon emissions in the first year than in the second and third years after rewetting. Short-term responses to rewetting, such as microorganism activation, availability of organic material due to desorption from soil matrices, and increased exposure of organic surfaces to microbes (Waddington et al. 2010), also affect the magnitude of carbon emissions in the first year of rewetting. Likewise, whether a year is drier or wetter can affect carbon emissions, as GWL fluctuates following precipitation, especially in ombrotrophic peatlands (Renou-Wilson et al. 2018); measurements taken only in drier years may therefore show higher CO_2 emissions compared to wetter years, and vice versa. As such, a longer monitoring period is needed following rewetting interventions to capture the overall trend of carbon emissions post-rewetting.

Our study found that the rewetting effect size in terms of CH_4 emissions showed an increasing trend from the first to the fourth year of monitoring after rewetting. In contrast, the rewetting effect size in terms of CO_2 emissions remained relatively constant (Fig. 6). Vegetation succession could explain the increased rewetting effect size for CH_4 emissions following hydrological restoration (Waddington and Day 2007). Rewetting interventions could induce the succession of vegetation (herbaceous) cover in rewetted areas, which could increase over the period since the intervention. Vegetation cover provides more labile organic matter for methanogens (Whalen 2005). A higher, more stable GWL close to the surface also enables the roots of herbaceous plants to be in the CH_4 production zone, meaning they can transport CH_4 to the peat surface and provide exudates for methanogens (Waddington and Day 2007; Zhong et al. 2020). However, the overall CH_4 emission effect size was dominated by individual effect sizes originating from the temperate zone, where herbaceous plants dominate vegetation cover; the temperate zone accounted for 44 individual effect sizes out of 67 effect sizes. As such, the relationship in Fig. 6 could be biased toward the temperate climate zone.

4.3 Meta-analysis challenges and implications for future field research

Meta-analysis has been demonstrated to be a powerful tool to understand the effect of rewetting on CO_2, CH_4 emission, and DOC concentration in peatland ecosystems. Using forest plots (Figs. 3, 4, and 7), for example, we can compare the consistency of treatment from a single study with other studies in just one figure. Meta-analysis can also quantify the magnitude of effect size based on a single study or subgroup and quantify overall effect size, which conventional reviews cannot do. Nevertheless, the quality of the meta-analysis depends on the datasets derived from individual studies. The most critical factors affecting the precision of a meta-analysis are sample size and study design (i.e., use of comparator sites) (Borenstein et al. 2009); larger sample sizes can yield more precise estimates than smaller sample sizes. In terms of comparator sites, before-after plots and paired sites can increase the precision of the effect size compared to studying two independent groups of the sample site. In reality, our study found that not all primary studies used before-after or paired sites as comparators in their study design. This meant that in our meta-analysis, we could only calculate effect size based on the 28 studies that applied before-after or paired sites. The paired site experimental design can be used as long as the measurement points being compared are located in similar micro-conditions (e.g., vegetation cover, micro-topography, or other abiotic/biotic factors). Along with improving the precision of effect size, using these study designs would also reduce heterogeneity (Crowther et al. 2010). Regarding geographical distribution, more studies on temperate climate zones were found than studies on boreal and tropical climate zones. This geographical gap has also been reported in other meta-analyses (Haddaway et al. 2014; O. Abbasi et al. 2020).

The most critical data extracted from the primary studies are mean, sample size, and standard deviation (SD) in the meta-analyses. Where these data were not provided in the original publication, it was necessary to contact the authors of the study; a complete monitoring report (including mean, SD, and sample size) in all studies would ease the process of meta-analysis. Depending on the completeness and quality of the original monitoring data, it is possible to use digitizing software (e.g., Web Plot Digitizer™, used in this study) to extract the data required for meta-analysis (Abbasi et al. 2020). Another challenge was encountered during initial data collection; most systematic reviews and meta-analyses rely on the titles of primary studies for searching. As such, primary studies without the key search terms (such as “rewetted” or “rewetting”) in their title may not have been identified during the database search, for example, studies conducted by Jauhiainen et al. (2008) and Clarke et al. (2020). Consequently, publication bias is highly likely to exist (see Figure S2 for publication bias using a funnel plot).

Although experimental studies on carbon emissions from peatlands are relatively abundant, especially temperate peatlands, we found that not many studies employed the before-after control-impact (BACI) design, CI design, or BA design. Using these study designs is critical if we want to observe the effectiveness of rewetting interventions and improve the accuracy of effect size estimation. Calculating the effect size from flux data collected from different site characteristics, i.e., land cover, management practice, and time measurements (e.g., seasonal, dry year, and wet year), would result in an inaccurate effect size. Therefore, it is encouraged to conduct more field research by applying the BACI design to similar study site characteristics. Moreover, there is also a gap with regard to monitoring times after rewetting interventions take place. Most studies only conduct monitoring in one particular year, either the first year following a rewetting intervention, or another specified year. To fill the gaps, we strongly recommend that experimental research be carried out over a longer timeframe to cover seasonal and annual variations, with adequate sample sizes and comparators at each site.

5 Conclusions

Based on our meta-analysis, rewetting previously drained peatlands has a reducing effect on CO_2 emissions by an average of -1.343 ± 0.36 Mg CO_2–C $ha^{-1}year^{-1}$ but shows an increasing effect on CH_4 emissions at an average of 0.033 ± 0.003 Mg CH_4–C $ha^{-1}year^{-1}$. This study thus suggests that rewetting could be a potential measure for avoiding CO_2 emissions from degraded peatlands, although more field-based data are needed to improve the accuracy of effect size quantification, especially in the case of net ecosystem CO_2 exchange (NEE) and carbon fluxes from DOC. Moreover, these data only provided carbon fluxes from the drained and rewetted peatland ecosystems. However, all carbon input and carbon outputs from the ecosystem should be measured in the field to evaluate the effect of rewetting on carbon balance and eventually on climate impact. We found that the measurement of heterotrophic respiration (R_h) was still limited; it is strongly recommended to measure the R_h in order to assess the effect of rewetting on carbon loss from peat.

In addition to GWL, we also found that the presence of and changes in vegetation cover following rewetting significantly influence CO_2 and CH_4 emissions, especially after a longer period following rewetting. To date, the experimental data are dominated by temperate peatlands; therefore, to reduce the bias in estimating the rewetting effect, carbon emissions data from boreal and tropical peatlands measured using the BACI study design are needed. Measurement of ancillary data, such as vegetation cover and composition, peat depth, and nutrient status, is also recommended since these data would improve the accuracy in quantifying the effect of the rewetting intervention.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11027-023-10046-9.

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Data availability All data used for this study are included in this published article (and its supplementary information files) in Doc and spreadsheet format.

Declarations

Conflict of interest The authors declare no competing interests.

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